

Relating aspen defoliation to changes in leaf area derived from field and satellite remote sensing data

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Abstract. Trembling aspen is the most important deciduous species in the North American boreal forest for which methods are needed to consistently map and monitor insect defoliation patterns to assess impacts on aspen health and productivity. The loss of foliage due to insect defoliation results in changes to leaf area index (Δ LAI) that were studied from both field and satellite image data for a large aspen tortrix (*Choristoneura conflictana* (Wlk.)) outbreak in boreal forest aspen stands in northern Alberta. Field estimates of defoliation for stands undergoing various levels of defoliation severity and both allometric and optical LAI-2000 measurements of leaf area index were collected and related to Landsat enhanced thematic mapper plus (ETM+) image data representing before- and after-defoliation events. This study was undertaken as part of the Climate Change Impact on the Productivity and Health of Aspen (CIPHA) research initiative that is taking place in western Canada. Field estimates of Δ LAI followed defoliation trends but with substantial scatter that may be attributed to the use of allometric estimates of predefoliation LAI and the subjective nature of visual defoliation assessment. Change estimates derived from both Landsat ETM+ scenes were statistically correlated (correlation $r = 0.84$, probability $P = 0.001$) with percent defoliation. Such an approach may be used in the future to calibrate LAI algorithms to other defoliated areas or to map the temporal intensity of these events as they occur.

Résumé. Le peuplier faux-tremble est l'espèce la plus importante de feuillus dans la forêt boréale nord-américaine pour laquelle des méthodes doivent être développées dans le but de réaliser la cartographie et le suivi en continu des patrons de défoliation par les insectes dans le contexte de l'évaluation des impacts de ces derniers sur la santé et la productivité des trembles. La perte de feuillage dû à la défoliation par les insectes entraîne des changements dans l'indice de surface foliaire (Δ LAI) qui ont été étudiés à partir de données de terrain et d'images satellitaires pour une pullulation de tordeuses du tremble (*Choristoneura conflictana* (Wlk.)) dans les peuplements de trembles de la forêt boréale, dans le nord de l'Alberta. Des estimations réalisées sur le terrain de la défoliation subie par des peuplements soumis à des niveaux de défoliation de sévérité variable et des mesures allométrique et optique LAI-2000 de l'indice de surface foliaire ont été collectées et reliées aux données Landsat ETM+ représentant des secteurs avant ou après la manifestation d'événements de défoliation. Cette étude a été réalisée dans le cadre du projet de recherche « climate change impact on the productivity and health of aspen » (CIPHA) présentement en cours dans l'Ouest canadien. Les estimations dérivées sur le terrain de Δ LAI étaient conformes aux tendances de la défoliation, mais montraient une dispersion substantielle pouvant être attribuée à l'utilisation d'estimations allométriques de LAI en période de pré-défoliation et à la nature subjective de l'évaluation visuelle de la défoliation. Les estimations du changement dérivées des deux scènes Landsat ETM+ étaient statistiquement corrélées ($r = 0.84$, $P = 0.001$) par rapport aux pourcentages de défoliation. Une telle approche pourrait être utilisée dans le futur pour étalonner les algorithmes LAI par rapport à d'autres zones de défoliation ou pour cartographier l'intensité temporelle de ces événements au moment même où ils se manifestent.

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Introduction

Trembling aspen (*Populus tremuloides* Michx.) is the most widely distributed North American tree species (Perala, 1990) and, from ecological and commercial perspectives, the most important deciduous tree species in the North American boreal forest (Peterson and Peterson, 1992; Hogg et al., 2002). Its geographic distribution extends from Atlantic Canada to the Pacific coast of Alaska, and as far south as Mexico (Peterson and Peterson, 1992). Aspen is especially important in the Canadian prairie provinces, as there has been a 10-fold increase in deciduous net merchantable harvest volumes from 1970 to 1995, most of which was attributable to aspen (Canadian Council of Forest Ministers, 1997). Without question, the

increasing utilization of aspen forests has increased the demands for information to help ensure sustainability of the resource.

There is evidence of poor aspen health characterized by reduced growth and dieback of aspen in different parts of North

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America, including southwestern Montana (Wirth et al., 1997), Saskatchewan and Manitoba (Zoltai et al., 1991; Hogg and Schwarz, 1999), northwestern Alberta (Hogg et al., 2002), and northeastern Ontario (G. Howse, Canadian Forest Service, personal communication, April 2002). Aspen dieback has been attributed primarily to repeated defoliation by insects, in combination with drought, severe early spring freeze-thaw events, and fungal pathogens (Zoltai et al., 1991; Hogg and Hurdle, 1995; Hogg et al., 2002; Brandt et al., 2002). Forest tent caterpillar (*Malacosoma disstria* Hubner) and large aspen tortrix (*Choristoneura conflictana* (Wlk.)) are the most serious defoliators of aspen, often causing extensive defoliation of hardwoods (Ives and Wong, 1988; Rose and Linquist, 1997; Hall et al., 1998). Outbreaks of these insects often last from 1 to 6 years (Cerezke and Volney, 1995). Consecutive years of severe defoliation can cause a substantial reduction in tree growth and eventually lead to tree mortality (Hildahl and Reeks, 1960; Churchill et al., 1964; Brandt, 1995). In the prairie provinces, the most current estimate of average annual losses from reduced growth and tree mortality caused by forest tent caterpillar and large aspen tortrix is 4.1 million cubic metres of wood (Brandt, 1995) or about 820 thousand tonnes of carbon per year. Model simulations show that under climate change, increased severity of drought could interact with insect defoliation to cause widespread decline in the future productivity and health of aspen forests of western Canada (Hogg, 1999; 2001). Furthermore, we can expect these interactions to exacerbate the problem because global change may cause demonstrable changes in the frequency and intensity of pest outbreaks (Volney and Fleming, 2000).

There is a critical need to consistently map and monitor the spatial location and dynamics of insect defoliation to provide information for prescribing pest management practices and to assess their impacts on aspen health and productivity. Aerial sketch-mapping has been the most widely used technique in forest health assessments (Ciesla, 2000) and has long been used to map and monitor aspen defoliation (Simpson and Coy, 1999). Aerial surveys, however, are not accurate enough to be used for relating defoliation (the mapped quantity) to impact (the quantity of growth and wood volume loss) (MacLean, 1990), hence the need for alternative approaches to this problem. The main factors attributable to concerns about aerial sketch-mapping accuracy include its subjectivity and repeatability, reliance on operator experience, and the influence of weather conditions prior to and during observations (MacLean and MacKinnon, 1996; Ciesla, 2000). As a result, the use of digital airborne and satellite remote sensing have been widely explored for detecting, mapping, and monitoring insect defoliation (Leckie and Ostaff, 1988; Franklin and Raske, 1994; Royle and Lathrop, 1997; Radeloff et al., 1999; Franklin, 2001, pp. 307–308).

The basis for using remote sensing data to detect defoliation damage lies in observing changes in spectral reflectance of forest canopies between two dates (Ahern and Leckie, 1987). The challenge is in defining a spectral basis for damage class limits, a critical problem to be resolved if consistent detection

and mapping of defoliation severity are to be achieved. This application creates the need to ensure image preprocessing can be undertaken to eliminate effects from variability in atmospheric and sensor calibration conditions. Compounding this challenge is the problem of spectral response from background understory vegetation (Guyot et al., 1989) that will increase as the amount of defoliation and dieback increases, unless defoliation is so severe that even understory vegetation is removed.

Defoliation and dieback are morphological conditions of damage that will have an influence on a tree's vegetative biomass or leaf area. Although the use of remote sensing has attained variable success at addressing forest health problems, there has been considerably more attention and success directed at mapping leaf area index (LAI) (Wulder et al., 1996; Franklin, 2001, pp. 280–285; Chen et al., 2002; Fernandes et al., 2003). LAI has been defined as half the all-sided green leaf area per unit ground surface area projected on the horizontal datum (United Nations Food and Agriculture Organization, 2002). LAI is considered a fundamental biophysical measure of the forest canopy due to its governing role in many ecophysiological processes (Running et al., 1989). It is related to stand productivity due to its role in regulating gas exchange, canopy light interception, evapotranspiration, and photosynthesis (Monteith and Unsworth, 1990). To date, there have been relatively few studies that have explored the sensitivity of leaf area measures to vegetative canopies that were subject to defoliation and other environmental stressors (Burton et al., 1991; Hunt et al., 1999). Recent studies, however, have reported good correspondence between percent crown dieback and aspen LAI (Hogg and Schwarz, 1999). Establishing a consistent relationship between ground-based estimates of percent defoliation and optical measurements of LAI is considered the fundamental base upon which its relationship to remote sensing images can be established.

The objective of this study was to test the hypothesis that defoliation is related to changes in leaf area measured both in situ and by remote sensing. To meet this objective, a study was undertaken during the summer of 2001 in northern Alberta where a large aspen tortrix outbreak was taking place. Two questions explored in this study were as follows: (i) Are in situ measurements of relative changes in LAI related to field-based estimates of defoliation? (ii) Are remote sensing based estimates of relative changes in LAI related to field-based estimates of defoliation?

Methods

Study area and site selection

The study area consists of plots located near the town of High Level in north-central Alberta situated at 58.5°N, 116.2°W (Figure 1). The area is considered part of the Wetland Mixedwood Subregion in the north and Dry Mixedwood Subregion in the south of the Natural Regions of Alberta and is characterized by nearly level to undulating terrain (Achuff,

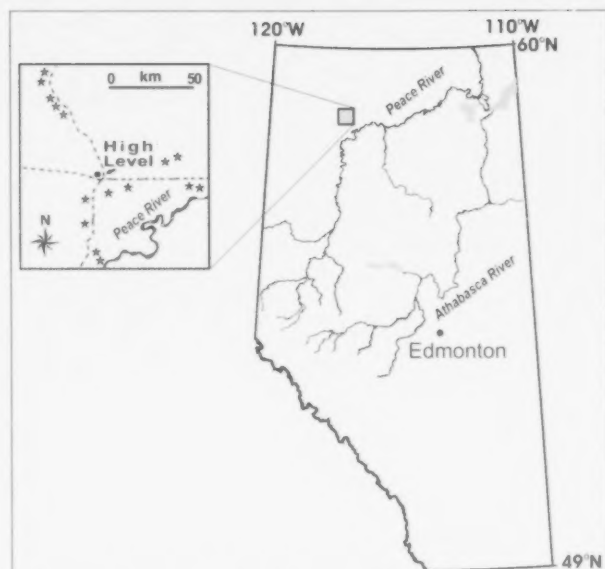


Figure 1. Location of the study area and stands sampled in the field. Two plots were established in each stand that were at least 60 m apart.

1992). Surficial materials are predominately glaciolacustrine, overlain by organic and till deposits in the Wetland Mixedwood Subregion and mostly till as ground moraine in the Dry Mixedwood Subregion (Achuff, 1992).

The field plots were located in the Mixedwood (B.18a) and southern extents of the Hay River sections (B.18b) of the Boreal Forest Region (Rowe, 1972). The species occurring depended on moisture and site conditions and were characterized by mixtures of trembling aspen (*P. tremuloides*), balsam poplar (*Populus balsamifera* L.), and white spruce (*Picea glauca* (Moench) Voss). White spruce is a successional tree species that tends to increase in stand composition as succession occurs in aspen or balsam poplar dominant stands.

This study is part of a long-term research project called Climate Change Impacts on the Productivity and Health of Aspen (CIPHA) that has been initiated to monitor changes in aspen health based on a network of field plots located in the three prairie provinces, British Columbia, and the Northwest Territories. The High Level area was selected because of a reported outbreak of large aspen tortrix that has been severely defoliating many trembling aspen stands. The current outbreak provided the opportunity to test the concept of a defoliation, leaf area, and remote sensing change monitoring approach to mapping aspen damage.

Plot location and classifying defoliation in the field

An aerial survey was initially undertaken by an experienced forest health rater to locate stands that were being defoliated to nil to light (<35%, including 0%), moderate (35–70%), and severe (>70%) levels as defined in the Alberta Land and Forest Service Aerial Survey Manual. Defoliation was sketch-mapped

onto 1 : 250 000 scale topographic maps and used as an aid in locating stands for plot establishment. The study was focused on relatively pure deciduous stands of aspen and balsam poplar and, to the extent possible, an approximately equal number of stands were selected in each of the three broad defoliation classes based on the results of the aerial survey. Two plots each were established in 15 stands that were at least 60 m apart and well within stands to minimize the influence of variable species composition or structures surrounding the stand. Plots were also placed at least 60 m away from roads or the entry point into the stand to minimize stand edge effects on defoliation measures. At each plot centre, a variable radius plot prism sweep with a basal area factor (BAF) of 2 was undertaken and the diameter recorded for each tree sampled. Using a BAF 2 prism most closely approximates a sampling probability proportional to tree frequency that was considered most appropriate for subsequent LAI estimation. Although measurement of every tree such as in fixed-area sampling would be preferable when attempting to correlate stand allometrics to leaf area, we did not observe significant ingress in the stands that were sampled. For example, there was no statistical difference in LAI based on a sample of six plots where fixed-area plot measurements were compared with the prism sample (probability $P = 0.81$). A field classification of stand type for species composition, stand height (measured with a hypsometer), and crown closure (with the aid of a spherical densiometer at four random locations) was undertaken at each plot to Alberta Vegetation Inventory specifications for the purposes of stand characterization (Resource Information Division, 1991). Estimates of defoliation were based on mean defoliation ratings of 10–20 randomly selected trees per plot during the period 22–25 June 2001. Defoliation of individual trees was visually estimated with the aid of binoculars to 10 percent classes (Michaelian et al., 2001). The geographic location of each plot was recorded with the aid of a Trimble Pro-XR global positioning satellite receiver whose data were subsequently differentially corrected to within 5 m of its true location with local base station data.

Determining leaf area index from field and optical methods

One of our objectives was to relate the field estimate of defoliation to the change in LAI (Δ LAI) caused by defoliation. Thus, Δ LAI was determined as the difference between LAI of the stand estimated before defoliation and the optical measurements of LAI at the time of defoliation. Because aspen defoliation has been taking place for more than 1 year, it was not possible for direct or optical measures of LAI before defoliation occurred. Consequently, at each plot, a method was needed to determine what the leaf area might have been in the absence of defoliation. The before-defoliation LAI was estimated by first using a published allometric equation to estimate LAI at the individual tree level based on the stem diameter for boreal aspen from the southern study site of the Boreal Ecosystem–Atmosphere Study (BOREAS) (Gower et

al., 1997). Given that the plots were also located in the Boreal Forest Region, it was assumed the functions developed by Gower et al. (1997) would provide a reasonable estimate of tree leaf area for aspen. Prism cruising formulas were then used to scale the tree leaf area to LAI based on the following procedures:

- (1) estimate aspen tree leaf area for each tree selected from the BAF 2 prism sweep in each plot using the equation

$$\log_{10}(\text{leaf area}) = a + b[\log_{10}(\text{tree diameter})]$$

where $a = -2.011$, $b = 2.611$, the adjusted coefficient of determination $r^2 = 0.905$, the mean square error = 0.014, and the logarithmic correction factor = 1.038 (Gower et al., 1997);

- (2) for a BAF of 2, the plot radius factor (PRF) = 0.3535, and for each tree within a given plot, compute its plot area Ait as

$$\text{Ait} = \frac{\pi(\text{dbh} \times \text{PRF})^2}{10\,000}$$

where dbh is the diameter at breast height in centimetres;

- (3) compute the sum of leaf area per hectare for all trees in a given plot as

$$Y_i = \sum \frac{\text{leaf area}}{\text{Ait}}$$

- (4) determine LAI for each plot by scaling the leaf area per hectare to leaf area per square metre as

$$\text{LAI} = \frac{Y_i}{10\,000}$$

A LI-COR LAI-2000 was used to optically measure LAI in the field near the culmination of larval feeding during the period 26–28 June 2001. The LAI-2000 is an optical instrument that measures the light penetration through the canopy with five quantum detectors arranged in concentric rings to capture light attenuation at mean zenith angles of 7°, 23°, 38°, 53°, and 67° (LI-COR Inc., 1991). Although the LAI-2000 has five concentric rings, readings were taken from only the fourth ring. Using all five rings (0–75°) or the first four rings (0–58°) may violate Miller's theorem compared to only using ring 4, as information about the leaf angle distribution is not needed at a single view angle (Warren-Wilson and Reeve, 1959). Leblanc and Chen (2001) reported that use of the fourth ring minimized the multiple scattering of light inside the canopy, which can cause underestimation of LAI. Their findings also showed that the effective LAI retrieved from the fourth ring is well correlated with the retrieved effective LAI from all five rings, with a coefficient of determination (R^2) of 0.99.

LAI-2000 readings were obtained at 1.3 m above ground and at 10 locations within the stand at each plot location along two parallel transects that were 50 m long and 10 m between each reading. Each LAI-2000 measurement has a footprint that extends 1.32 times the height of the tree for the fourth ring. The LAI-2000 measurements were made under defoliation conditions similar to those for the plots. Under the assumption that the foliage spatial distribution is random and the woody material is negligible, the LAI-2000 provides an estimate of the effective leaf area for vegetation canopies based on the measure of gap fraction at these zenith angles (Chen et al., 1997; Gower et al., 1999). Chen et al. (1997) demonstrated that optically derived LAI was comparable to LAI derived from allometric relationships found from destructive sampling up to an LAI of six and was therefore selected for LAI measurement during the defoliation stage. The LAI is calculated from inversion of gap fraction measured by comparing LAI-2000 readings inside and outside stands (LI-COR, Inc., 1991; Leblanc and Chen, 2001) and then subtracting from the "before" defoliation LAI to derive an estimate of ΔLAI , the change in LAI as a result of defoliation. Because defoliation is a relative measure (percentage), ΔLAI has to be normalized by the LAI from the before-LAI estimate. Descriptive statistics, correlation coefficient, and a linear nonparametric Thiel-Sen regression model fitting method were undertaken to explore the trends and relationships between the field estimate of defoliation and relative ΔLAI .

As a comparison with the optical LAI measurements, we also estimated LAI of the aspen-dominated tree layer in each plot using the litter trap method (e.g., Chason et al., 1991). In early summer 2001, bucket traps with an inner diameter of 21 cm and a height of 20 cm were installed at the same locations where optical LAI measurements were made. The trap size was considered reasonable given the small size of the aspen leaves, with an average area of about 15 cm², or <5% of the 346 cm² area sampled by each bucket trap. The buckets had holes in the bottom to allow drainage and were anchored at ground level with stakes. The litter was collected from the bucket traps after leaf fall during mid to late October 2001 (total of 8–10 traps per plot, with overall loss rate of about 10% due to animal damage). Litter samples were oven-dried (50°C) and stored at room temperature prior to analysis. The litter was sorted according to species, weighed, and then corrected for changes in moisture content based on weight changes in a reference sample of dry aspen leaf litter. For each species and each plot, the dry mass of litter fall was expressed on a ground area basis (kg·m⁻²) by dividing the mean litter dry mass per bucket by the area sampled. Estimates of tree LAI were made based on the assumption of a fixed specific leaf area (SLA, m²·kg⁻¹) for the current-year litter of each species, as determined from previous analyses of litter (E.H. Hogg, unpublished data) at two mature aspen stands in Saskatchewan (Hogg and Hurdle, 1997). The values of SLA used were 11.5 and 12.4 m²·kg⁻¹ for aspen and balsam poplar, respectively.

Satellite remote sensing data

Two Landsat scenes were used in this study and were selected based on the (i) occurrence of coincident field-based measurements, (ii) specific biological window needed to capture the stage of defoliation and, (iii) coverage with no cloud-smoke or haze contribution. The scene-selection procedure was an important process toward defining a statistical relationship between field-based measurements of defoliation and remotely sensed vegetation indices. The biological windows for selection of image dates were carefully considered because the temporal analysis of insect defoliation and monitoring require multiseasonal data acquisition (Muchoney and Haack, 1994). This problem is more critical with the use of space-borne sensors because the acquisition of an appropriate cloud-free image may be nonexistent for weeks at a time. In this case, the scene-selection procedure directly considered the large aspen tortrix temporal window of biological activity, since peak damage by the pest occurs in mid-June before the insect begins to pupate (Prentice, 1955). Although this temporal window was coincident with the field measurements, no scenes were available during this time. The closest alternatives acquired by Landsat enhanced thematic mapper plus (ETM+) in early July were deemed satisfactory, as they matched all three criteria defined previously. Thus, to capture changes in surface reflectance and LAI attributable to forest defoliation, a 21 July 1999 (worldwide referencing system (WRS) path 46, row 19) scene was used to assess predisturbance estimates of leaf area. A scene acquired on 10 July 2001 was used to link coincident ground-based measurements of leaf area and defoliation to remotely sensed measurements and used for post-disturbance analysis. Although several more scenes were considered for use, only these two were relatively cloud free over the plots and fit the defined criteria.

The Landsat images were processed to retrieve top-of-atmosphere directional reflectance. The Landsat ETM+ data corresponded to level 1G at-sensor radiance systematic corrected data that were processed using the product generation system (PGS) processor by Radarsat International. Radiometric calibration was performed using header information provided in Landsat ETM+ header files. An iterative dense dark vegetation (DDV) atmospheric correction approach was applied to both scenes in this study using information extracted from selected DDV pixels across various spectral wavelengths to determine the contribution of aerosols influencing the pixel radiances recorded at the satellite sensor. The approach described here is similar to the method described by Liang et al. (2001), with several modifications that were found to be more appropriate for Canadian landscapes. The 6S radiative transfer code (Vermote et al., 1997) was used iteratively to determine an estimate of surface reflectance given top-of-atmosphere reflectance and an estimate of aerosol optical depth. This approach provided a systematic and repeatable method for both radiometric calibration and atmospheric correction of multitemporal Landsat imagery, as these factors are essential to

produce precise estimates of LAI based on the broadband spectral vegetation indices used to map LAI (Fernandes et al., 2003).

Both Landsat scenes were georeferenced to the Lambert conformal conic projection using nearest-neighbour, first-order transformations. To retrieve image-based LAI and minimize geolocal errors in locating the field plots in the imagery, a 3×3 average LAI was extracted based on the location of plot centre.

LAI map generation

To generate remote estimates of LAI from each Landsat scene, previously established relationships that validate in situ LAI measurements to remote LAI were used. These relationships were determined using structural regressions between Landsat reflectance measurements and in situ optical LAI measurements over 56 deciduous stands (Fernandes et al., 2003). The algorithms were calculated from remote measurements of the infrared simple ratio (ISR) vegetation index:

$$ISR = \frac{\rho_{ETM+ \text{ band } 4}}{\rho_{ETM+ \text{ band } 5}} \quad (1)$$

where $\rho_{ETM+ \text{ band } 4}$ and $\rho_{ETM+ \text{ band } 5}$ represent the surface reflectances (ρ) for Landsat ETM+ spectral bands 4 and 5, respectively.

Empirical regressions were used with the ISR to estimate image LAI except for regions designated as crops or grasslands based on a coregistered 1 km land cover (Cihlar et al., 2003) and land use intensity map (Kerr et al., 2002). Currently, agricultural and grassland areas are still mapped using the simple ratio due to the lack of calibration data (Fernandes et al., 2003). These areas were screened prior to defoliation assessment using land cover products so that the higher image-based LAI uncertainties over these regions would not likely impact the results of our study.

Recent error analysis studies report Equation (1) to be a more robust indicator for LAI retrieval (Fernandes et al., 2003; Butson et al., 2002) than the simple ratio or reduced simple ratio previously used in Chen et al. (2002) because atmospheric effects are minimized at longer spectral wavelengths. The total error budget for LAI retrieval based on the ISR was documented at the Landsat scale by Butson et al. (2002).

Results

Stand characterization and defoliation conditions

Of the 30 plots established in the field, 14 were rated nil to light and 16 were rated moderate to severe during the aerial survey. All plots were established in predominately deciduous stands, and their structures were similar across crown closure (70% versus 62%) and stand height (16.5 m versus 17.0 m) between the nil to light and moderate to severe damage classes,

respectively, (**Table 1**). The larger crown closure and shorter stand height may suggest the nil to light stands were slightly younger, given the higher stocking typically associated with younger aspen stands (Peterson and Peterson, 1992). On average, the stands rated nil to light were 17% (standard deviation (s) = 8.2%) defoliated compared with 82% (s = 8.0%) for those rated moderate to severe, and the defoliation was progressive by class with ratings for nil, light, moderate, and severe of 9, 22, 78, and 85%, respectively. These estimates were based on subjective ratings and are therefore subject to error; however, validation of the estimates is difficult without direct sampling of foliage, which is both tedious and time-consuming to undertake.

A problem encountered in the field that made defoliation rating difficult was the early refoilation of the aspen trees in late June. Aspen refoilation usually occurs in mid to late July following the completion of larval feeding (Ives and Wong, 1988). As a result, stands that appeared to be moderately defoliated during the aerial survey were actually severely defoliated but refoiling when assessed in the field, and were therefore more correctly defined as moderate to severe. Those plots without field defoliation ratings in **Table 1** are those that were most difficult to rate because of significant refoilation and were therefore removed from analysis. In addition, in four plots the optical measure of LAI during defoliation was actually larger than the estimate of LAI before defoliation. A possible reason for this occurrence was the uncertainty associated with the allometric approach used to estimate the predefoliation LAI; this approach was used only on trees that were taller than about 8 m, compared with the LAI-2000 measurements that measured LAI at 1.3 m above ground. Although these plots were not removed from further analysis, they were statistical outliers during the modeling of Δ LAI (**Figure 2**).

Defoliation and Δ LAI

Overall, defoliation and Δ LAI were statistically and positively correlated ($r = 0.59$, $P = 0.005$). Based on a scatterplot to illustrate the distribution of the defoliation and Δ LAI data, however, there are clearly two distinct groups that corresponded to the nil to light and moderate to severe defoliation levels (**Figure 2**). A linear nonparametric Thiel-Sen regression between defoliation and Δ LAI variables resulted in a root mean square error of 28% (**Figure 2**). This value was considered reasonable given the clustering of data observations into two predominant groups, the plus or minus one 10% class field defoliation rating allowable for forest health raters, and the effect of refoilation conditions encountered in this study. The range of Δ LAI values within each group was small relative to the range of defoliation classified in the field. For the nil to light class, the relative Δ LAI ranged from 0 to 0.42 for defoliation that ranged from 10 to 30%. This level of uncertainty will reflect both the errors in estimation of Δ LAI because of the use of allometric predefoliation LAI estimates and differences in interpretation of defoliation from ocular damage assessment and quantitative LAI measurements. For

the moderate to severe class, Δ LAI ranged from 0.21 to 0.76 for defoliation that ranged from 70 to 93%. Although we expected larger and more tightly clustered Δ LAI values at the higher defoliation levels, both the woody component and any tall shrub or treed understory may have inflated the apparent LAI values to partially mask the higher defoliation condition that was evident in the overstory.

A larger sample size would be necessary to further refine the relationship between defoliation and Δ LAI. Taking LAI-2000 measurements during the leaf-off period to estimate the woody component and a means of accounting for the tall understory vegetation would also be necessary in addition to incorporating measurements such as those from the tracing, radiation, and architecture of canopies (TRAC) to account for possible clumping in deciduous canopies (Chen et al., 1997). Although we did not encounter significant clumping in this study due to the importance of gap fraction measurements of pure deciduous stands under defoliation conditions, it could be more important in future studies because of the diversity of species compositions and stand conditions that could be encountered. Timing the ground-based defoliation estimates more closely with vegetative phenology and when the defoliation damage is most visible may also improve the relationship. Although timing was carefully planned for this study, refoilation had occurred much earlier than expected.

LAI estimates from leaf litter fall

The collections of leaf litter from the plots during the autumn following defoliation confirmed the deciduous tree layer was dominated by aspen (>98%), with a minor (<2%) component of balsam poplar. The LAI estimates based on leaf litter reflect the canopy characteristics immediately before the main period of leaf fall in late September, about 3 months after the optical LAI measurements were made. The mean LAI at each plot ranged from 1.19 to 3.16, with standard deviations from 0.16 to 0.57. The corresponding standard errors (ranging from 0.06 to 0.22) were consistently <10% of the mean LAI for all plots, suggesting that the number of traps established was appropriate.

The estimates of LAI based on litter traps were moderately well correlated with the optical LAI measurements in the same plots (sample size $N = 24$, $r = 0.735$, $P = 0.001$), despite the difference in the seasonal timing and in the potential sources of error underlying the two methods. The optical LAI-2000 and litter-based LAI were strongly correlated and linear in relationship (**Figure 3**). The degree of scattering in this relationship presumably reflects both actual changes in LAI during the season (increases from continued re-leafing of the canopy and possible decreases from other foliage-feeding insects) and the inherent errors associated with each method. The litter-based estimates of LAI were not substantially larger than expected in the plots that had experienced moderate or severe defoliation in early June. For the plots assessed as having >70% defoliation, the mean litter-based LAI of 1.56 was similar to the mean measurements optical LAI (1.43), thus

Table 1. Summary of mensurational and LAI data.

Plot No.	Plot name	Species composition ^a	Crown closure (%)	Stand height (m)	Defoliation class from aerial survey	Mean ground-based defoliation estimate (%)	Estimated LAI before defoliation ^b	Optical LAI during defoliation	Estimated proportional decrease in LAI ^c	LAI from litter traps after defoliation
1	hln1-1	Aw10	85	14.9	Nil	9.5	2.79	2.79	0.00	
2	hln1-2	Aw10	83	14.7	Nil	9.5	2.58	2.58	0.00	2.36
3	hln2-1	Aw10	74	16.9	Nil	9.5	3.20	2.58	0.19	2.40
4	hln2-2	Aw10	71	14.0	Nil	8.5	2.29	3.58	-0.56	2.51
5	hln1-1	Aw10	55	15.6	Light	30.5	2.62	2.16	0.18	2.16
6	hln1-2	Aw10	50	16.6	Light	19.5	2.03	1.93	0.05	2.20
7	hln2-1	Aw10	77	17.6	Light	16	3.27	2.26	0.31	3.16
8	hln2-2	Aw10	57	18.3	Light	27.5	2.02	2.26	-0.12	2.19
9	hln3-1	Aw10	65	16.1	Light	11.0	2.77	2.16	0.22	1.97
10	hln3-2	Aw10	67	15.4	Light		2.56			2.56
11	hln4-1	Aw10	70	20.8	Light	20.2	3.12	1.82	0.52	2.35
12	hln4-2	Aw10	73	18.1	Light		2.97			2.40
13	hln5-1	Aw10	76	15.8	Light	28.5	2.11	1.99	0.06	1.61
14	hln5-2	Aw10	81	16.6	Light		2.12			2.51
15	hlms1-1	Aw10	42	16.3	Moderate-severe	72.0	2.45	1.33	0.46	1.70
16	hlms1-2	Aw10	40	16.0	Moderate-severe	84.5	3.48	1.49	0.57	1.26
17	hlms2-1	Aw10	53	18.9	Moderate-severe	73.5	2.78	1.42	0.49	1.88
18	hlms2-2	Aw10	57	15.5	Moderate-severe	77.0	2.99	1.71	0.43	1.92
19	hlms3-1	Aw10	55	17.5	Moderate-severe	81.7	2.56	1.80	0.30	1.69
20	hlms3-2	Aw10	52	22.8	Moderate-severe	82.3	1.97	2.29	-0.16	1.70
21	hls1-1	Aw10/A11Sw10	75	13.0	Severe	77.5	1.84	1.12	0.39	1.25
22	hls1-2	Aw10	44	14.6	Severe		1.75			1.52
23	hls2-1	Aw9Sw1	68	14.8	Severe	69.5	2.03	1.36	0.33	1.39
24	hls2-2	Aw10/A8Sw10	69	16.5	Severe		2.01			1.19
25	hls3-1	Aw9Pb1	85	17.7	Severe	92.0	3.13	0.79	0.75	1.37
26	hls3-2	Aw9Pb1/A8Sw10	73	20.1	Severe	87.0	1.85	1.38	0.25	1.52
27	hls4-1	Aw10	76	20.0	Severe	90.5	3.91	0.92	0.76	1.47
28	hls4-2	Aw8Pb2	61	20.3	Severe	85.5	3.09	1.25	0.60	1.54
29	hls5-1	Aw10	68	14.1	Severe	89.0	1.06	1.47	-0.39	1.56
30	hls5-2	Aw10	78	16.9	Severe	92.5	2.15	1.69	0.21	1.55

^aAw10, 100% aspen overstory; Aw10/A11Sw10, 100% aspen overstory and A density (7–30%); 11 m tall 100% white spruce in the understorey; Aw9Sw1, 90% aspen and 10% white spruce overstorey; Aw10/A8Sw10, 100% aspen overstory and A density (7–30%); 8 m tall 100% white spruce in the understorey; Aw9Pb1, 100% aspen and 10% balsam poplar overstorey; Aw9Pb1/A8Sw10, 100% aspen and 10% balsam poplar overstorey and A density (7–30%); 8 m tall 100% white spruce in the understorey; Aw8Pb2, 80% aspen and 20% balsam poplar in the overstorey.

^bEstimated from stem diameters using allometry equation for aspen from BOREAS southern study area in Saskatchewan (Gower et al., 1997).

^cCalculated as $\Delta \text{LAI}/\text{estimated LAI before defoliation}$, using optical LAI measurements during defoliation period in June 2001.

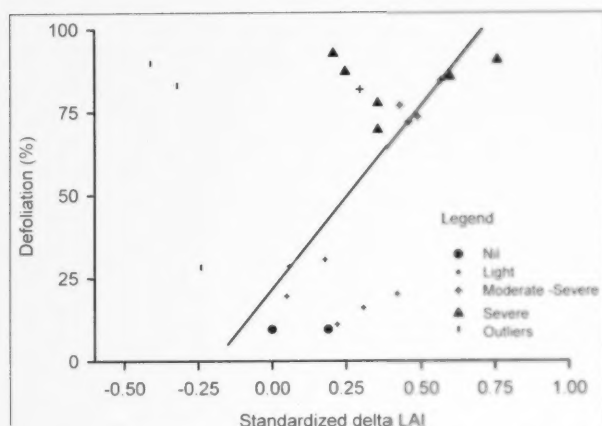


Figure 2. Relationship between defoliation and in situ relative Δ LAI (delta LAI) with the Thiel-Sen regression line.

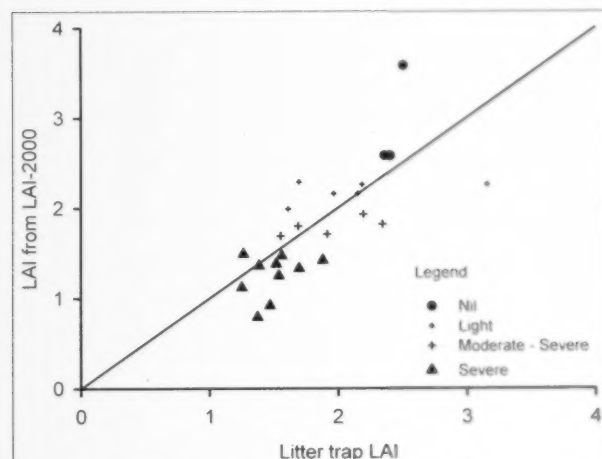


Figure 3. Relationship between optical LAI-2000 measurements taken with defoliation and LAI determined from leaf litter traps. A 1:1 relationship line has been plotted, and the two measurements were significantly correlated ($r = 0.74$, $P = 0.00004$).

suggesting that significant re-leafing had not occurred after the initial defoliation assessments.

Defoliation and image-based LAI

Figure 4 illustrates colour composites of the two Landsat ETM+ scenes together with LAI images over regions not masked by clouds. Image-based estimates of LAI were found to be relatively scattered, with residuals of ± 0.5 LAI for in situ LAI values below 1.5 and then linearly related above that level. The variability in low LAI may be partially due to the presence of understory shorter than 1.3 m that was not measured in the field. Also, the in situ LAI estimates were not corrected for variability in woody area or canopy clumping. These two effects should cancel out, to some extent, for dense stands, but

we have no experience with these effects in low-density defoliated stands.

We applied the Thiel-Sen nonparametric regression given the presence of potential measurement errors in both response (in situ LAI) and regressor (thematic mapper (TM) LAI) variables (Kendall and Stuart, 1967). A regression on the entire data set with no constraints resulted in a slope of 0.78, with a 1 sigma confidence interval that ranged from 0.65 to 0.92, and an intercept of 0.28, with a 1 sigma confidence interval that ranged from 0.30 to 0.11. This suggests that TM LAI retrievals have some bias because the Thiel-Sen regression slope is robust to 28% of the data being outliers. The small sample size makes it difficult to determine the cause of this bias. Examination of the scatter about the 1:1 line indicates maximum absolute errors of 1 LAI unit with a root mean square deviation of 0.37 LAI unit (**Figure 5**). This is a promising validation of the LAI algorithm given that it had been developed for Canada-wide applications. **Figure 6** indicates that the relationship between the change in LAI estimates by satellite and in situ data is somewhat less precise than the relationship between LAI estimates for a single date. The root mean square deviation from the 1:1 line was 18.6% (decrease in LAI). The Thiel-Sen line fit had a slope of 1.55, with a 1 sigma confidence interval that ranged from 1.36 to 1.78. The slope reduced, however, to 1.26 when the offset was constrained to zero to compensate for the relatively small number of nondefoliated plots. In any event, both line fits served to reduce the mean square deviation about the fitted line by less than 2%. The poor precision in this relationship was expected, given that it represented the comparisons of paired differences based on four independent measurements with errors tending to add in a Euclidean fashion.

The association of field estimates of defoliation, based on human observers, to changes in image LAI suggest that it is possible to classify low and high defoliation levels using the ISR-based LAI algorithm (**Figure 7**). Furthermore, an exponential fit ($N = 14$, $r = 0.84$, $P = 0.001$), although speculative given the absence of points in the middle range, suggests there may be a saturation in the defoliation response at both high and low levels. The saturation of changes in LAI for severe defoliation is because of the absence of further changes in the canopy signal as leaves are lost and the increasing influence of understory effects on top of canopy reflectance. The flat response in defoliation with small changes in LAI may, in part, be due to limitations in the ability to undertake accurate assessments in lightly damaged stands that had not been visited prior to the defoliation event. The variability in Δ LAI for low levels of defoliation also reflects precision errors in the LAI retrieval algorithms.

There was no consistent relationship between aspen defoliation and ETM+ estimates of Δ LAI when algorithms were based on the simple ratio algorithm (R.A. Fernandes, unpublished data). This lack of relationship may be because of both the sensitivity of SR-based LAI estimates to atmospheric correction errors (e.g., Fernandes et al., 2003) and the increased sensitivity of the SR to understory variability in comparison to

the indices based on the shortwave infrared band (Brown et al., 2000).

The plot level results do not provide information regarding the spatial pattern of defoliation estimates from ETM+. For example, it is likely that defoliation will be patchy, so isolated outbreaks far from defoliation epicentres may indicate commission errors. Unfortunately, ancillary high-resolution maps of the defoliation patterns were not available to quantify the degree of agreement with the image map. However, a qualitative assessment of the defoliation patterns was undertaken. **Figure 7** shows a fine-scale comparison of both ETM+ colour composites and a LAI change image for the subregion indicated in **Figure 4**. The latter was of interest given that the shortwave infrared band will theoretically vary as a function of understory moisture content and canopy moisture found in leaves (Ceccato et al., 2002a; 2002b). The region of

severe defoliation corresponding to sample plots within the boxed region in the centre of the image was correctly mapped homogeneously as an area of large LAI decrease that was attributable to defoliation (**Figure 7**). Additionally, most other areas of LAI decrease (depicted in red tones in **Figure 8**) occur in patches corresponding to aspen stands. There are a number of smaller isolated areas with moderate LAI decrease (<0.5 LAI indicated in yellow tones in **Figure 8**) that do not correspond to aspen stands. These areas then indicate the level of precision in the algorithm for this typical subimage. Interestingly, the LAI change image also showed areas of regrowth over regions of disturbance.

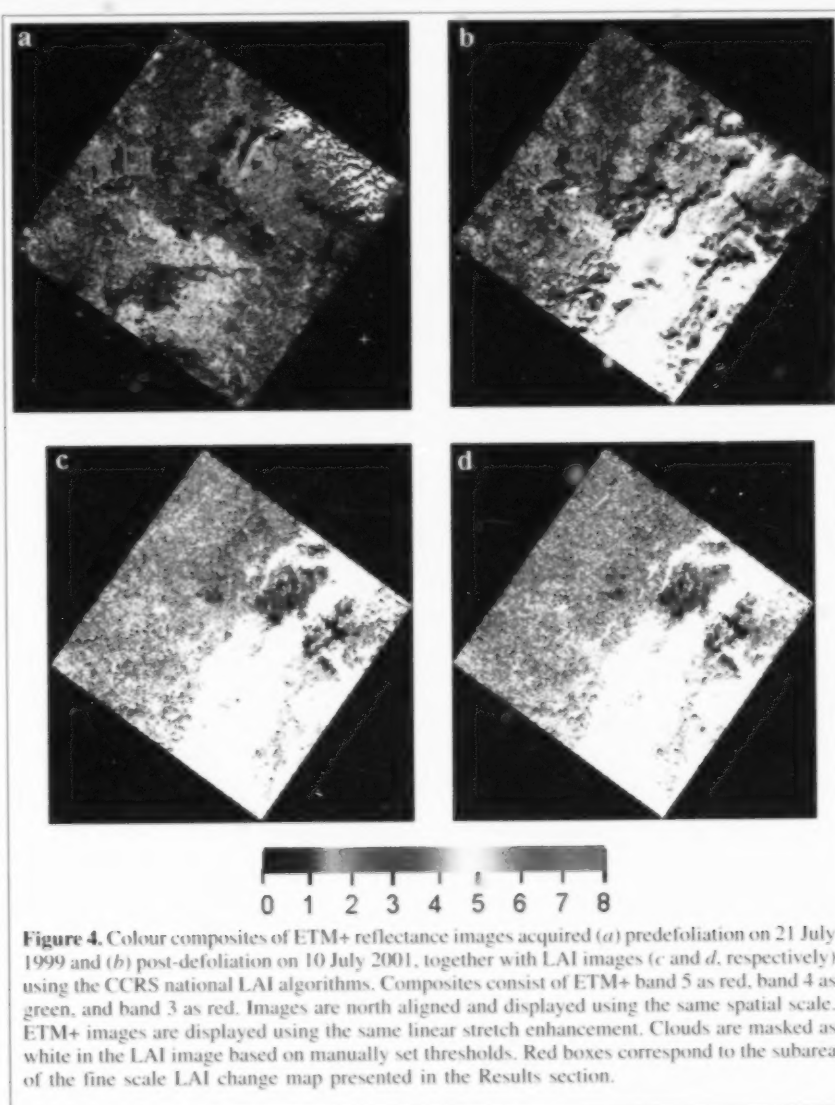


Figure 4. Colour composites of ETM+ reflectance images acquired (a) predefoliation on 21 July 1999 and (b) post-defoliation on 10 July 2001, together with LAI images (c and d, respectively) using the CCRS national LAI algorithms. Composites consist of ETM+ band 5 as red, band 4 as green, and band 3 as red. Images are north aligned and displayed using the same spatial scale. ETM+ images are displayed using the same linear stretch enhancement. Clouds are masked as white in the LAI image based on manually set thresholds. Red boxes correspond to the subarea of the fine scale LAI change map presented in the Results section.

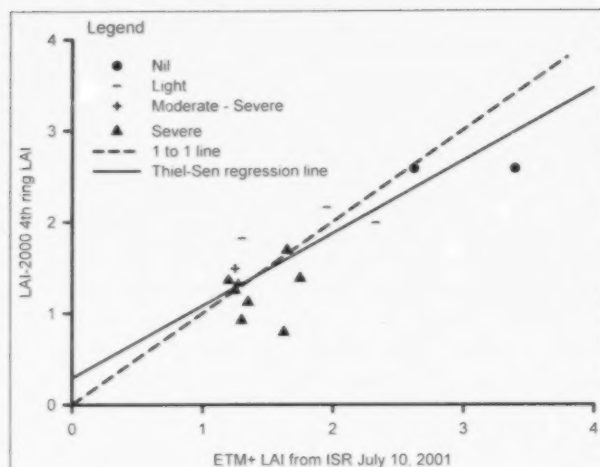


Figure 5. Scatterplot of ETM+ LAI estimates derived by using the CCRS national LAI algorithm with the infrared simple ratio (ISR) versus in situ LAI estimates from LAI-2000 measurements using the fourth ring only over aspen plots. Both LAI estimates correspond to overstory measurements. In situ measurements have not been corrected for clumping area index other than through averaging multiple samples per plot. A 1:1 line and the Thiel-Sen regression line are included.

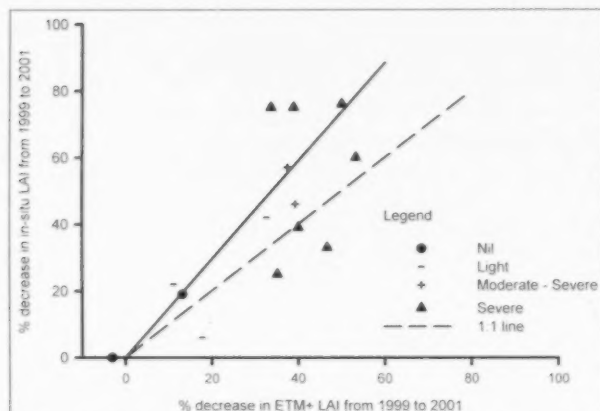


Figure 6. Comparison of in situ remote sensing based estimates of change in LAI between 1999 and 2000 over cloud-free study plots. A Thiel-Sen regression line fit and the 1:1 line are included. In situ estimates are based on a difference of allometric (predefoliation) and optical (post-defoliation) LAI estimates. Remote sensing estimates are derived using a difference in LAI maps from temporal Landsat ETM+ imagery.

Discussion

Field defoliation and Δ LAI

Although there was a statistically significant correlation between field-rated aspen defoliation and Δ LAI, the change in LAI caused by defoliation, there were several factors that

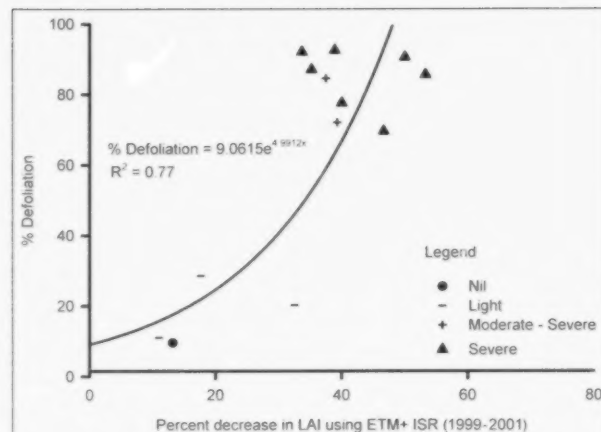


Figure 7. Change in LAI derived from ETM+ infrared simple ratio (ISR) index algorithms versus in situ estimates of defoliation by manual survey over aspen plots in cloud-free regions of both ETM+ scenes. A negative change in LAI implies a drop in LAI between 1999 and 2001 ETM+ scene overpasses. A nonlinear fit is provided for illustrative purposes only, given the lack of points at moderate levels of defoliation.

complicated efforts toward defining this relationship. These factors include the assessment of defoliation in the field, procedures for estimating Δ LAI, and field conditions during LAI measurement, such as stand composition and structure, understory vegetation, and refoliation.

Perhaps one of the most challenging factors is obtaining precise estimates of stand defoliation. The field assessment of defoliation is typically subjective (Ciesla, 2000) and is impossible to quantify precisely without destructive sampling. In this study, our interest in a precise defoliation assessment was important for determining its relationship with changes in leaf area. Forest health raters are trained and calibrated to estimate defoliation to within plus or minus one class or 10% (Michaelian et al., 2001). This type of rating results in a tolerance range of 30%, which, although sufficient for most forest health applications, is too broad when attempting to quantify its relationship with empirical leaf area tools and remote sensing derivatives. Deriving methods to improve the field measures of defoliation would directly influence its relationship and mapping from remote sensing, and this would likely improve the basis for quantifying the extent and impact of defoliation at the landscape level.

There are at least three potential sources of error in the estimation of Δ LAI, including (i) the methods used to estimate a before-defoliation LAI, (ii) the measurement of LAI during defoliation, and (iii) the potentially confounding influence of understory vegetation and nonphotosynthetic materials on satellite-based estimates of overstory LAI.

First, the use of published allometrics in the estimation of a before-defoliation LAI is only appropriate to the extent that the functions employed are applicable to the species and ecological area of interest. Some validation of this approach in nondefoliated stands would have helped to verify the accuracy

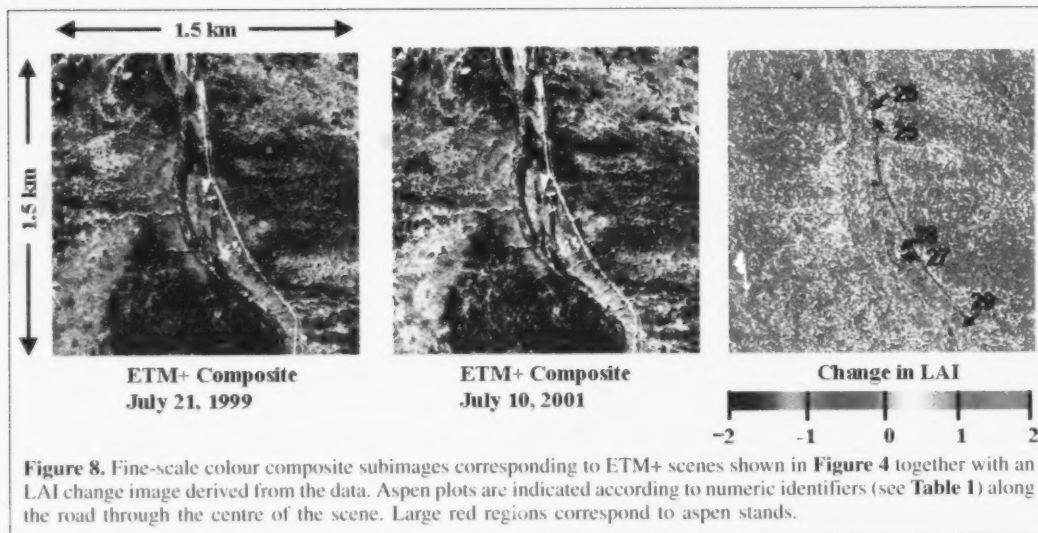


Figure 8. Fine-scale colour composite subimages corresponding to ETM+ scenes shown in **Figure 4** together with an LAI change image derived from the data. Aspen plots are indicated according to numeric identifiers (see **Table 1**) along the road through the centre of the scene. Large red regions correspond to aspen stands.

of this method. Ideally, ΔLAI should be measured directly, by including ground-based LAI measurements in the year prior to a major defoliation event, but the problem in anticipating the location of future insect outbreaks makes this measurement logistically difficult. As a result, the use of published allometrics is likely the most feasible approach in the determination of predefoliation LAI. In this context, although we employed a prism sample to select trees for measurement in this study, the likelihood of encountering more variable stand conditions with trees of different sizes would suggest that fixed-area samples be used. Fixed-area samples measure all trees that would provide a more representative measure of basal area and, consequently, LAI than a sampling procedure that only selected the largest trees.

Among the ground-based methods of measuring LAI, the optical methods are most suitable under conditions of major structural changes in the canopy, such as those occurring during insect defoliation. The optical methods such as the LAI-2000, however, rely on the assumption of random distribution of foliage elements within the field of view of measurement. Recent research suggests this assumption may not be valid for aspen canopies and that some measure of foliage clumping is necessary for the correct estimation of LAI (Chen et al., 1997; Kucharik et al., 1997). This would be particularly relevant in open density stands where leaf area tends to be clustered where trees are established. Further, the LAI-2000 measures diffused radiation interception without the distinction between woody and photosynthetically active materials (LI-COR, Inc., 1991). As such, a potential confounding factor in LAI measurement is that the woody component may become more important as the defoliation level increases (**Figure 9**). In pure deciduous stands, one approach to estimate the woody contribution to leaf area might be its measurement during the leaf-off period. Its effect is not entirely additive, however, because during the



Figure 9. Visible canopy gaps in plot hls5-1 (**Table 1**) as a result of defoliation and stand composition. At the higher defoliation levels, the woody component becomes a more important factor in the measurement of effective leaf area.

growing season the woody material is mostly masked by foliage.

An alternative approach to address these potential sources of error is to combine optical measurements with a more direct method such as destructive sampling of foliage or by autumn collection of leaf litter (Chason et al., 1991; Cutini et al., 1998). The latter method is much less labour-intensive but has the limitation that it can only provide LAI estimates for deciduous species immediately before leaf fall. Although we found a moderately good correlation in the LAI measurements between the LAI-2000 and litter trap estimates (**Figure 3**), more detailed studies are needed to improve the accuracy of these methods for monitoring changes in LAI under various conditions of leaf phenology, stand characteristics, and level of defoliation. Also,

our litter-based LAI estimates were based on the assumption of a constant SLA for the litter of each species, but variation in SLA may be anticipated within and among stands, and as a result of changes during senescence and decomposition of litter prior to collection. Lastly, there is a need to examine how understory vegetation, especially tall shrubs, affects satellite-based measurements of LAI in the tree canopy.

Defoliation and image-based LAI

One of the most important factors governing the use of remote sensing for assessing insect damage, including defoliation, is timing (Hall et al., 1995; Ciesla, 2000). Although we would not have expected the refoliation to produce very high LAI values, its occurrence raises issues that the timing and magnitude of the second flush are very important from the perspectives of (i) defining the "window" when remote sensing can be applied for detection of defoliation, (ii) assessing the impact of defoliation on C uptake and productivity, and (iii) determining the influence of defoliation on seasonal water vapour flux (transpiration) and energy partitioning at the landscape scale.

The ISR-based LAI estimates from an ETM+ scene corresponded relatively well with in situ measurements. The uncertainty in canopy clumping and woody area may explain the observed bias, but the relatively small sample size suggests further validation is required. It is remarkable that an LAI algorithm developed using a calibration sample of a number of broadleaf species across Canada and applied without manual intervention other than cloud masking was able to perform in a relatively unbiased manner. Absolute LAI retrieval errors will include both uncertainties in estimation of the vegetation index and the LAI regression algorithm we have applied. Butson et al. (2002) suggest that uncertainties in LAI estimation due to ISR calibration are approximately 5–15% in scenes where sufficient dense dark vegetation targets are available to perform atmospheric correction. Fernandes et al. (2003) report that the regression algorithm has an additional uncertainty on the order of ± 1 LAI unit in the worst case. The mean relative absolute error for the data (22%) in **Figure 5** falls well within this range of combined uncertainties for the range of 1–3 LAI units found in the study plots.

The computation of a change in LAI over time should substantially reduce uncertainties in the regression algorithms related to variability in species and understory encountered in the Canada-wide data set used for calibration. There is an outstanding concern as to the impact of understory growth and structural changes within the canopy on the remote signal change. Both the absolute LAI validation and the relationship between LAI change and defoliation, however, suggest these effects were not substantial over our study area. A more rigorous experiment using optical in situ LAI measurements before and during defoliation could verify this statement. The absence of moderately defoliated plots limited our ability to completely address the question as to how ETM+ based changes in LAI are related to defoliation. The data presented

here suggest a monotonic change is present with sufficient precision to allow for detection of two defoliation categories (nil to light and moderate to severe). More tests of this approach at aspen defoliation sites in other areas of the CIPHA study are underway to determine if the relationship observed is universal or image or region specific.

Theoretically, the change in LAI with time includes an additional uncertainty due to background phenological variability such as the refoliation effect and surface moisture variability. Our use of similar overpass dates and careful screening to avoid precipitation events immediately before the overpass minimizes this effect. A useful system for defoliation screening or mapping based on ETM+ data would have to include some means of accounting for phenological changes between epochs. Two approaches are currently being investigated to address this problem: using coarse-resolution, daily repeat, polar-orbiting satellites to track large spatial changes in LAI with time; and using multiple ETM+ scenes over the same region to quantify the background noise levels due to changes in LAI over regions where it is known a priori that defoliation is not occurring.

Visual assessment of the spatial pattern of changes in LAI seems sufficiently stable to identify large stands undergoing defoliation while screening isolated patches with lesser levels of LAI change. Progress can be made in including both ancillary geospatial information (e.g., location of aspen stands and previous outbreaks) and the ecology of pest outbreaks to screen for false alarms. Nevertheless, our initial study suggests that even simple nonspatial thresholding (say $\text{LAI} > 1$ unit) will identify "defoliation hot spots". Validation using airborne defoliation sketch-maps and interpretation of aerial photographs taken at the appropriate phenological windows will be necessary in subsequent studies.

Conclusions

The research problem was to estimate changes in leaf area that were attributable to defoliation from both field and satellite image perspectives. The relationship between observer-rated defoliation and ΔLAI , the change in LAI as a result of defoliation, was defined in this study. Although there is a statistically significant relationship between defoliation and relative ΔLAI ($r = 0.59$, $P = 0.005$), three areas requiring further work were identified: a more quantitative approach to rating defoliation severity, verification of allometric models employed in estimating before-defoliation LAI, and a measure of clumping and nonphotosynthetic materials to improve the sensitivity of ΔLAI estimation.

A strong relationship ($r = 0.86$, $P = 0.001$) between ΔLAI on the satellite image and defoliation was observed for the study sites. More work is needed to determine the sensitivity of this relationship over aspen-dominant mixed stands in other regions across Canada and with other dates of ETM+ scenes acquired after the defoliation event. A practical problem is that one must be able to find and measure defoliation in situ and have a cloud-free overpass at the same time. The combination of these

constraints makes experimental design challenging for defoliation monitoring via remote sensing-based LAI. Temporal LAI validation is a costly and long-overdue issue that needs further consideration.

Based on the ETM+ image results generated from this study, the moderate to severe defoliation patterns can be clearly separated from the level of background noise through simple thresholding. A priori stratification using land cover and land use information can screen out other noise sources such as harvest or thinning. Some spatial context will be needed in future work to separate changes in LAI due to insect infestation versus changes due to other factors such as harvesting and thinning operations. A first step in this direction may be the use of image-based change detection algorithms, such as those applied for forest fire burn mapping (Fraser et al., 2000), to identify both spatial and temporal anomalies in LAI. Ideally, this spatial approach would combine models of pest outbreak to screen for anomalies due to other disturbances. Although the results in this early work are encouraging, addressing the future work areas identified to improve the defoliation-ΔLAI-image relationships will no doubt greatly improve the potential for operational mapping of insect defoliation patterns.

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